

# Prospects for Observing the Standard Model Higgs Boson Decaying into $b\bar{b}$ Final States Produced in Weak Boson Fusion with an Associated Photon at the LHC

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One of the primary goals of the Large Hadron Collider is to understand the electroweak symmetry breaking mechanism. In the Standard Model, electroweak symmetry breaking is described by the Higgs mechanism which includes a scalar Higgs boson. Electroweak measurements constrain the Standard Model Higgs boson mass to be in the 114.4 to 157  $\text{GeV}/c^2$  range. Within this mass window, the Higgs predominantly decays into two b-quarks. As such, we investigate the prospect of observing the Standard Model Higgs decaying to  $b\bar{b}$  produced in weak-boson-fusion with an associated central photon. An isolated, high  $p_T$ , central photon trigger is expected to be available at the ATLAS and CMS experiments. In this study, we investigated the effects originating from showering, hadronization, the underlying event model, and jet performance including b-jet calibration on the sensitivity of this channel. We found that the choice of Monte Carlo and Monte Carlo tune has a large effect on the efficacy of the central jet veto and consequently the signal significance. A signal significance of about 1.86 can be achieved for  $m_h = 115 \text{ GeV}/c^2$  with  $100 \text{ fb}^{-1}$  of integrated luminosity which correspond to one year at design luminosity at 14 TeV  $pp$  collisions.

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## I. INTRODUCTION

One of the primary goals of the Large Hadron Collider (LHC) is to investigate the electroweak symmetry breaking mechanism which is explained in the Standard Model (SM) [1], by the Higgs mechanism [2]. Although the Higgs boson has yet to be discovered, there are several theoretical and experimental constraints on the Standard Model Higgs mass. The lower bound on the Higgs mass of 114.4  $\text{GeV}/c^2$  at 95% Confidence Level (C.L.) is constrained by direct measurements at LEP [3]. Additionally, the upper bound is constrained indirectly by several global fits to electroweak measurements. A global fit of the electroweak data as a function of Higgs mass reported by LEP Electroweak Working Group on the favors a Higgs mass centered at  $87^{+35}_{-26} \text{ GeV}/c^2$  and a 95% one-sided C.L. on the upper limit at 157  $\text{GeV}/c^2$ . Similarly, the GFitter results using a global fit which includes the constraints from the direct Higgs boson searches yields an upper limit on the Higgs mass of 153  $\text{GeV}/c^2$  at 95% C.L. [4]. Within the favored Higgs mass region the range excluded at 95% C.L. for a SM Higgs is  $163 < m_H < 166 \text{ GeV}/c^2$  as determined by the Tevatron [5].

There are several channels, such as  $H \rightarrow \gamma\gamma$ ,  $H \rightarrow \tau\tau$ , and  $H \rightarrow Z^*Z$ , which are expected to discover a light SM Higgs at the LHC with approximately  $30 \text{ fb}^{-1}$  of 14 TeV  $pp$  data [6, 7]. However, additional studies will be required to confirm if the new resonance is indeed the SM Higgs.

In this paper, we study the prospect for observing the process  $H \rightarrow b\bar{b}$  which will be instrumental in determining spin, CP, gauge coupling, and Yukawa

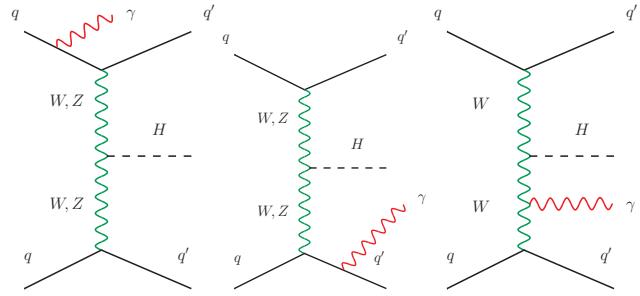


FIG. 1: Tree-level t-channel Feynman diagrams for Higgs boson production in the process  $pp \rightarrow H\gamma jj$ . Here,  $q$  and  $q'$  represent quarks ( $u, d, s, c$ ) while  $q$  and  $q'$  are the same when a  $Z$  boson is exchanged.

coupling of the Higgs candidates. Distinguishing  $H \rightarrow b\bar{b}$  from the large QCD background is the main challenge for this analysis. At the LHC, the largest production cross section for Standard Model Higgs boson is gluon fusion ( $gg \rightarrow H$ ); the next largest is Weak-Boson-Fusion (WBF). The distinct kinematical and QCD properties of the WBF production, described in Section II, provide discrimination from QCD processes. We resolve the challenge of triggering on a four-jet final state by requiring an associated photon. Specifically, we investigate the sensitivity to a light SM Higgs Boson produced in association with a photon in WBF production, as shown in Figure 1, in 14 TeV  $pp$  collisions at the LHC. The photon provides a simple unprescaled trigger for the four-jet + photon final state as originally proposed by E. Gabrielli, *et al.* [8].

The Monte Carlo samples generated for this study

are described in Section III. In Section IV, the selection criteria used in the analysis are presented. The event selection is composed of photon trigger and identification (Section IV A), jet performance studies (Section IV B), weak-boson-fusion jet identification (Section IV C), b-jet identification and light jet fake rates (Section IV D), b-jet calibration (Section IV E), and central jet veto (Section IV F). In Section V, the systematic uncertainties associated with the Monte Carlo generator cross-sections and the choice of showering, hadronization, and the Underlying Event (UE) model are presented. Finally, the results and summary of this analysis are discussed in Sections VI and VII respectively.

## II. WEAK BOSON FUSION

The WBF process consists of weak gauge bosons radiated from the quark partons fusing to become a Higgs boson. The quarks scatter with sufficiently high  $p_T$  to be detected in the forward hadronic calorimeters of ATLAS and CMS. The Higgs boson is produced centrally as are the two b-jets. The kinematics of this four-jet topology, one WBF forward, one backward and two central jets, is exploited to suppress the four-jet background from QCD processes. Additionally, jet activity in signal events tends to be forward of the WBF jets. QCD radiation is at small angles with respect to the WBF quarks with no color connection between the scattered quarks. In contrast, QCD production involves color charge exchange between the scattered quarks. Consequently, the QCD radiation takes place over large angles and populates the central detector region. The optimization of the selection criteria is described in Section IV.

## III. EVENT SAMPLES AND SIMULATION

In this paper, the signal and background Monte Carlo events were produced in two stages using ALPGEN [9] and PYTHIA [10]. The ALPGEN generator was used in the first stage to produce the parton four-vectors and to determine the leading order cross-sections. The hard partonic interaction used at the generator stage was evaluated using the CTEQ6L1 structure functions [11] for the colliding protons. Several kinematic cuts were applied on the signal and background samples in the analysis and are listed in Table I. Within this paper  $\Delta R$  is defined as  $\Delta R_{kl} = \sqrt{\Delta\eta_{kl}^2 + \Delta\phi_{kl}^2}$ ,  $\Delta\eta_{kl} = \eta_k - \eta_l$ ,  $\Delta\phi_{kl} = \phi_k - \phi_l$  of the  $k^{th}$  and  $l^{th}$  parton, where  $\eta$  is the pseudo-rapidity and  $\phi$  is the azimuthal angle. To provide inclusive background samples without double counting, a jet-parton matching scheme referred to as the MLM prescription [12] was applied. In this paper, the jet-parton ( $jp$ ) matching efficiency is referred to as the MLM efficiency. The matching requirements used for this analysis were  $p_T(j) > 17.5$  GeV/c,  $\Delta R_{jp} < 0.7$ , and  $|\eta_j| < 6.0$ .

$p_T(j) > 15$ GeV/c	$ \eta_j  < 5.5$	$\Delta R_{jj} > 0.7$
$p_T(\gamma) > 15$ GeV/c	$ \eta_\gamma  < 3.0$	$\Delta R_{\gamma j} > 0.7$ $\Delta R_{\gamma b} > 0.7$
$p_T(b) > 15$ GeV/c	$ \eta_b  < 5.5$	$\Delta R_{bj} > 0.7$ $\Delta R_{b\bar{b}} > 0.7$

TABLE I: ALPGEN generator level kinematic cuts applied on signal and background.

PYTHIA was used for the second stage of the Monte Carlo production to perform the heavy particle decays, including the Higgs decay, showering, hadronization, and the UE model. The resulting cross-sections are provided in Sections III A and III B.

### A. Higgs Signal

The Feynman diagrams for the signal process are shown in Figure 1. Three mass points were used to scan the range in which the Higgs decaying to two b-quarks is dominant. The nominal parameterization of the factorization and renormalization scales was set to  $\mu_F^2 = \mu_R^2 = m_h^2 + p_T^2(\gamma) + \sum p_T^2(j)$ , where  $p_T(\gamma)$  and  $p_T(j)$  are the transverse momentum of the photon and of the jets, respectively. The sum over the transverse momentum includes all final state jets. Table II shows the cross-section and branching fraction obtained for each Higgs mass point. The Higgs branching fraction was evaluated with the program HDECAY [13].

$m_h$ [GeV/c $^2$ ]	115	125	135
$\sigma(H\gamma jj)$ [fb]	69.7	67.0	52.8
$\text{BR}(H \rightarrow b\bar{b})$	0.73	0.61	0.43
$\sigma \times \text{BR}$ [fb]	50.9	40.9	22.7

TABLE II: Cross sections for the  $H\gamma jj$  signal for 14 TeV  $pp$  collisions. Additionally, the Higgs boson branching fraction to  $b\bar{b}$  using HDECAY [13].

### B. Backgrounds

The event topology consists of four jets and an associated photon. Consequently, the largest backgrounds originate from QCD processes with radiated photon(s).

The primary background is the  $b\bar{b} + 2\text{partons} + \gamma$  process, shown in Figure 2, which has the same final state particles, that is, one photon, two b-jets, and 2 additional jets. Additionally, the large background cross-section relative to that of the signal makes the combinatorial invariant mass of the two b-quarks very challenging to suppress. We also considered the  $b\bar{b} + 1\text{parton} + \gamma$  in which a secondary jet can originate from showering, hadronization, or the UE model. The  $b\bar{b} + n\text{partons} + \gamma$  were produced such that the 1 parton sample is exclusive

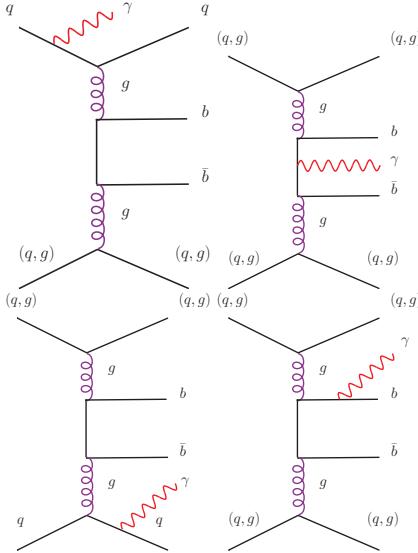


FIG. 2: Representative classes of Feynman diagrams contributing, at parton level, to the background process  $pp \rightarrow bbjj\gamma$ . Here  $q$  and  $g$  represent the quarks ( $u, d, s, c$ ) and gluon, respectively.

and the 2 partons sample is inclusive. These samples were produced using the factorization and renormalization scales  $\mu_F^2 = \mu_R^2 = \sum m_T^2$ , where the sum includes all final state partons,  $m_T$  is the transverse mass defined as  $m_T^2 = m^2 + p_T^2$ , and  $m$  is the mass of the parton.

The  $Z(\rightarrow q\bar{q})+n\text{parton}+\gamma$  sample was considered because the high side of the  $Z$ -boson mass peak can potentially contaminate the signal region. The samples were produced such that all quark flavors were included except for the top quark. For similar reasons as the  $b\bar{b}+n\text{partons}+\gamma$  background, we produced a one parton exclusive sample and a 2 partons inclusive sample. The factorization and renormalization scales were set to  $\mu_F^2 = \mu_R^2 = m_Z^2 + p_T^2(\gamma) + \sum p_T^2(j)$ .

In addition to background processes which have legitimate b-quarks, we also considered light quark and gluon QCD processes which fake reconstructed b-jets. We only considered processes with large cross-sections because of the low probability of two light jets faking two b-jets. Consequently, we produced  $n\text{parton}+\gamma$  samples, with an exclusive 3 partons and inclusive 4 partons sample. We neglected the  $n\text{parton}+2\gamma$  processes which are suppressed by an additional factor of  $\alpha_{em}$ .

The ALPGEN cross-sections, the MLM efficiencies, and effective cross-sections for the aforementioned background samples are presented in Table III.

Parton #	$\sigma$ [pb] @14 TeV	MLM $\epsilon$ [%]	$\sigma' = \sigma \times (\text{MLM } \epsilon)$ [pb]
$b\bar{b}+n\text{parton}+\gamma$			
1	1088	37.9	452
2	658	35.7	235
$n\text{parton}+\gamma$			
3	45789	20.5	9387
4	17595	17.8	3130
$Z(\rightarrow q\bar{q})+n\text{parton}+\gamma$			
1	27.1	40.6	11.0
2	18.2	44.5	8.10

TABLE III: Cross-section, MLM efficiency, and the effective cross-section for background processes as determined using ALPGEN/PYTHIA for 14 TeV  $pp$  collisions.

#### IV. EVENT SELECTION

In this section, we present the analysis strategy to measure the Higgs boson using the weak-boson-fusion production mechanism with an associated photon production. A Higgs event in this process is characterized by two geometrically well separated jets, a prompt photon, and the Higgs decay products. In Section IV A, our assumptions on photon trigger and photon identification are summarized. The jet performance is presented in Section IV B. Identification strategies for the weak-boson-fusion jets are described in Section IV C. In this analysis, we required the Higgs to decay into two b-quarks. Consequently, Section IV D summarizes the b-jet identification and fake rate estimation from c-jets and light jets. We discuss the b-jet calibration in Section IV E. In Section IV F, we investigate the possibility of applying a veto on additional central jets given the present theoretical models for the UE.

In order to maximize the signal significance, we performed a ranked optimization using signal over square root of background ( $S/\sqrt{B}$ ) as the figure-of-merit. For the signal, we used an independent sample with a Higgs mass of  $115 \text{ GeV}/c^2$  and used the  $b\bar{b}+2\text{partons}+\gamma$  sample to estimate the full background. For the  $b\bar{b}+2\text{partons}+\gamma$  sample, we used events in sideband region invariant mass of the two b-jet's,  $m_{bb}$ , sideband which was defined as  $100 \text{ GeV}/c^2 < m_{bb} < 130 \text{ GeV}/c^2$  in order to avoid any bias.

##### A. Trigger and Photon Identification

An isolated tight  $25 \text{ GeV}/c$  transverse momentum photon trigger is assumed to be available at the LHC experiments. In addition, the trigger turn-on curve is expected to plateau very quickly requiring a modest increase in the transverse momentum of reconstructed pho-

tons. Consequently, for this analysis we required an isolated 30  $\text{GeV}/c$  transverse momentum photon within  $|\eta| < 2.5$ , corresponding to the coverage of the electromagnetic calorimeters in ATLAS and CMS [6, 7]. The photon is identified by matching all candidates to the matrix-element photon. Once the proper photon is identified, we removed any overlapping particles or jets within a  $\Delta R$  of 0.7. The  $p_T$  spectrum of the photons is shown in Figure 3.

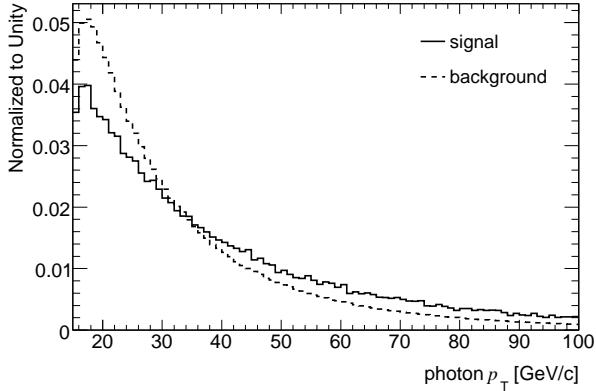


FIG. 3: Transverse momentum distribution of the associated photon for a 115  $\text{GeV}/c^2$  mass Higgs at 14 TeV collision energies.

## B. Jet Identification and Performance

In addition to the central photon, which provides a viable trigger option and reduces the cross section of the backgrounds, the only additional objects used for this analysis are jets. Consequently, the aim of this section is to study the effect of the jet performance on the potential to observe the  $H(\rightarrow b\bar{b})+2\text{jets}+\gamma$  channel.

The goal of jet reconstruction is to reproduce the 4-momentum of the original parton. However, the showering, hadronization, particle decays, and detector performance complicates this goal. In this section, we investigate the performance of jet algorithms at the hadronization level. In order to account for some detector effects, we excluded muons and neutrinos from the jet constituent input list as these particles are not measured by the calorimeter. Additionally, we excluded charged particles with  $p_T < 400 \text{ MeV}/c$  and neutral particles with  $p_T < 200 \text{ MeV}/c$ . For this study, we evaluated the performance of the ANTI-KT [14] and SISCONE [15] algorithms as provided in the SPARTYJET [16] package. For SISCONE we considered a cone radius of 0.4 and 0.7 (labeled as SISCONE7 and SISCONE4) and the aggregation distance of 0.4 and 0.6 for ANTI-KT (labeled as ANTI-KT4 and ANTI-KT6).

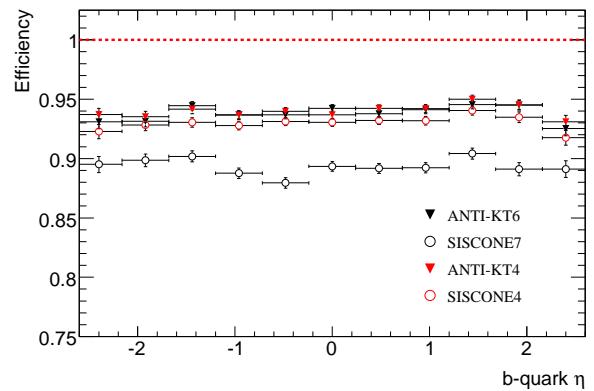


FIG. 4: Efficiency for b-quark reconstruction as a jet as a function of  $\eta$  using a 115  $\text{GeV}/c^2$  Higgs mass sample. The small asymmetry in  $\eta$  is due to the seeding/sorting of jets.

The results presented in this section were obtained using the signal Monte Carlo sample with a 115  $\text{GeV}/c^2$  Higgs mass<sup>1</sup>. We studied two performance requirements in order to compare the various jet algorithms and settings. These requirements are listed below.

1. The efficiency to identify each individual parton.
2. The ability to properly reconstruct the transverse momentum (linearity and resolution).

### 1. Efficiency

We considered four factors that can contribute to the jet reconstruction inefficiency

1. Parton constituents outside of the detector acceptance window.
2. Low transverse momentum partons leading to particles with insufficient energy after hadronization.
3. Neutrinos - which are not detected.
4. Small angular separation between outgoing partons resulting in a single jet.

To study the jet inefficiency for a single parton, we selected isolated quarks by requiring that no additional jets are within  $|\Delta\phi| < 1.4$ . Additionally, we defined a matched jet as the jet closest to the outgoing parton within  $\Delta R < 0.4$ . The efficiencies as a function of  $\eta$  for b-jets and WBF jets are shown in Figures 4 and 5, respectively. The effect of the detector acceptance window near  $\eta = 5$  is visible in Figure 5. The effect of

<sup>1</sup> The  $b\bar{b}+2\text{partons}+\gamma$  Monte Carlo samples yielded similar results.

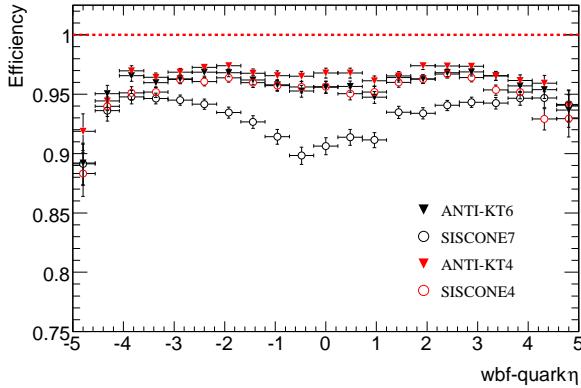


FIG. 5: Efficiency for WBF-quark reconstruction as a jet as a function of  $\eta$  using a  $115 \text{ GeV}/c^2$  Higgs mass sample. The small asymmetry in  $\eta$  is due to the seeding/sorting of jets.

inefficiency as a function of the initial parton transverse momentum can be seen in Figures 6 and 7. Here we required the b-quark and WBF quarks to be within  $|\eta| < 2.5$  and  $|\eta| < 4.5$ , respectively. We restrict the b-jet  $\eta$  window based on the tracking system coverage of CMS and ATLAS [6, 7]. The efficiency of the b-jets are lower than that of the WBF jets. The integrated jet reconstruction efficiency for each algorithm is given in Table IV. SISCONE7 exhibits inferior performance than the other three jet reconstruction algorithms whose performance are comparable.

Jet Algorithm	SISCONE4	SISCONE7	ANTI-KT4	ANTI-KT6
Four Jet Efficiency	69.6%	58.2%	72.3%	70.1%

TABLE IV: Jet efficiency for tagging the four signal jets with their appropriate  $\eta$  window.

In the scenario in which two quarks are emitted with a small relative angle, we investigated the efficiency of identifying two jets as a function of their  $\Delta R$  separation. For this study we required all four outgoing quarks to have  $p_T > 15 \text{ GeV}/c$ , both b-quarks to be within  $|\eta| < 2.5$ , and both WBF quarks to be within  $|\eta| < 4.5$ . Figure 8 shows the efficiency to reconstruct two b quarks as a function of  $\Delta R$ . Figure 9 shows the efficiency to reconstruct two WBF quarks as a function of  $\Delta R$ . In both Figures 8 and 9, the inefficiency at small  $\Delta R$  is due to the cone radius/aggregation distance of the jet reconstruction algorithm. For the b-jets, the low efficiency at large  $\Delta R$  is due to the correlation between  $\Delta R$  and the low  $p_T$  b-jets.

Similar to the individual jet efficiency the SISCONE7 configuration yields noticeably worse results than the other jet configurations. This is particularly true in the case of the two b-jet pairing in which the large cone size

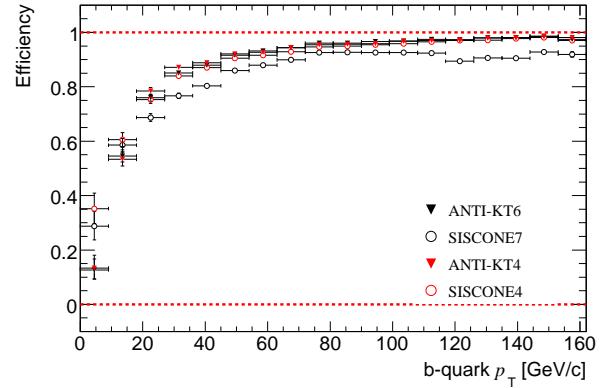


FIG. 6: Efficiency for b-quark reconstruction as a jet as a function of the b-quark  $p_T$  using a  $115 \text{ GeV}/c^2$  Higgs mass sample. Only events with  $|\eta| < 2.5$  were considered.

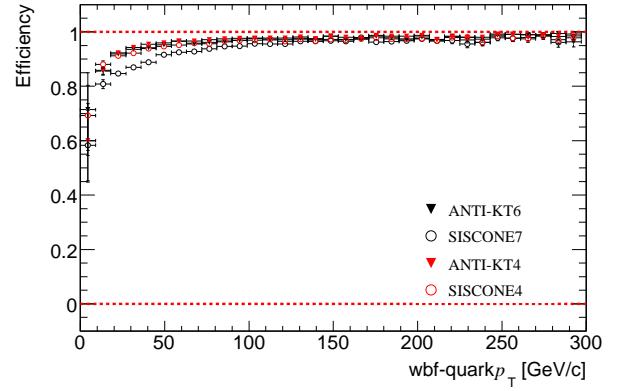


FIG. 7: Efficiency for WBF-quark reconstruction as a jet as a function of the WBF-quark  $p_T$  using a  $115 \text{ GeV}/c^2$  Higgs mass sample..

is problematic given the reduced  $\eta$  window. Again, the other three jet configurations yield similar results.

## 2. Linearity and Resolution

In addition to the efficiency, we considered the performance of the jet transverse momentum linearity and resolution for each jet configuration. The jet transverse momentum linearity and resolution was calculated using Equation 1.

$$\Delta p_T = \frac{p_T^j - p_T^p}{p_T^p} \quad (1)$$

Here  $p_T^j$  and  $p_T^p$  are the transverse momentum of the jet and outgoing parton, respectively. We parameterized the distributions with a double Gaussian function and used the Gaussian with the largest amplitude to provide

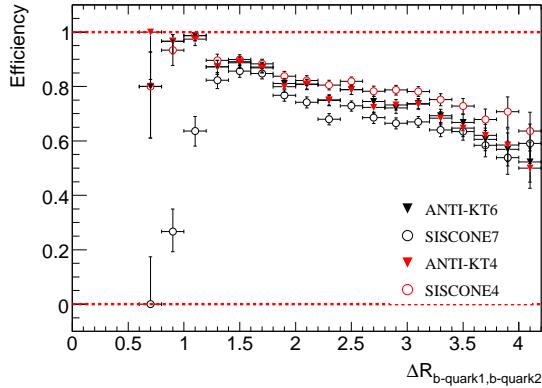


FIG. 8: Efficiency to reconstruct two b-quarks as two jets as a function of the  $\Delta R$  between the two quarks.

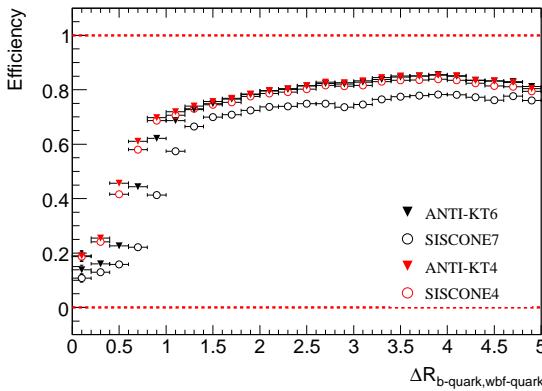


FIG. 9: Efficiency for a WBF-quark b-quark jet reconstruction as a function of the  $\Delta R$  between the two quarks.

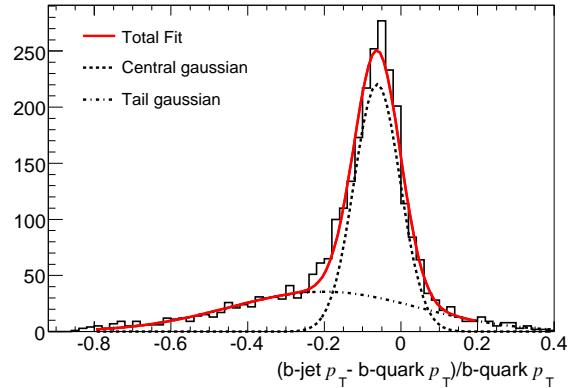


FIG. 10: Distribution of the  $p_T$  variable, defined in Equation 1, in one of the  $p_T$  slices of the b-quarks Monte Carlo sample. The result of the fit to the sum of two gaussians (Central gaussian + Tail gaussian) is also shown.

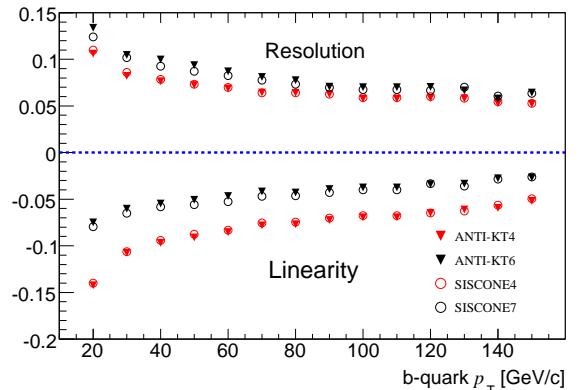


FIG. 11: Linearity and resolution (mean value and sigma of the central gaussian in the  $\Delta p_T$  fits) as a function of the b-quark transverse energy.

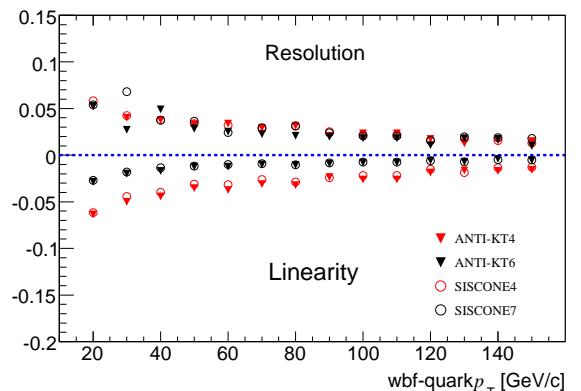


FIG. 12: Linearity and resolution (mean value and sigma of the central gaussian in the  $\Delta p_T$  fits) as a function of the WBF transverse energy.

the linearity and the resolution. An example of the double Gaussian fit is shown in Figure 10. Figures 11 and 12 show the linearity and resolution as a function of the  $p_T$  of the b-quark and WBF-quarks, respectively. From these distributions, we conclude that the SISCOME7 and the ANTI-KT6 provide the best linearity results without any noticeable degradation of the resolution compared to the other two configurations. Additionally, we observed a significant performance degradation of the b-quarks jet reconstruction compared to WBF-quarks. Consequently, additional corrections to the b-jets are required and are summarized in Section IV E.

In conclusion, the SISCOME4, ANTI-KT4, and ANTI-KT6 configurations gave similar efficiency and resolution results, however, ANTI-KT6 provides significant improvement in linearity. Consequently, we used ANTI-KT6 for the rest of this paper.

### C. Weak-Boson-Fusion Jet Identification

The geometrical topology of the WBF jets provides significant distinction between signal and background. In addition, this topology provides a clean separation between the WBF jets from the b-jets in signal events. This is particularly important when trying to reconstruct the Higgs mass from b-jet candidates since incorrectly identifying b-jets degrades the Higgs mass resolution.

Accordingly, we developed a WBF tagger which uses a likelihood ratio to distinguish the desired WBF jet pair from b-jet pairs within the signal. The likelihood ratio,  $y$ , is defined using the WBF jet pair likelihood ( $\mathcal{L}_v$ ) and the b-jet pair likelihood ( $\mathcal{L}_b$ ), as shown in Equation 2.

$$y = \frac{\mathcal{L}_v}{\mathcal{L}_v + \mathcal{L}_b} \quad (2)$$

Here,  $\mathcal{L}_{v/b}$ , is defined as the product of 1-dimensional probability density functions,  $P(x_i)$ , as shown in Equation 3, where  $x_i$  is the  $i$ th variable.

$$\mathcal{L}_{v/b} = \prod P_{v/b}(x_i) \quad (3)$$

Three geometrical variables were used in the likelihood ratio to identify the best WBF jet candidates. These variables are listed below and are shown in Figures 13, 14, and 15.

1. The absolute difference in pseudo-rapidity,  $|\Delta\eta_{ij}| = |\eta_i - \eta_j|$ .
2. The product of pseudo-rapidities,  $\eta_i \times \eta_j$ .
3. The 3-dimensional angle between the two jets,  $\theta_{ij}$ .

Here  $i$  and  $j$  correspond to the pair of WBF and b quarks candidates. The probability density functions used in the likelihood ratio were generated using matrix element distributions from an independent signal sample with a 115 GeV/c<sup>2</sup> Higgs mass. The WBF tagger is indifferent to the jet flavour, as such, it occasionally selects b-jets. We observed approximately 5% b-jet contamination in the signal samples after all signal selection cuts. Once two WBF jet candidates are identified, the following kinematic cuts are applied.

*Invariant Mass:* The majority of the QCD multi-jet background will produce ‘soft’ jets resulting in a low invariant mass compared to the two WBF jets from the signal, as shown in Figure 16. Consequently, we required the invariant mass,  $M_{jj}$ , of the WBF jet candidates to be greater than 695 GeV/c<sup>2</sup> in order to reduce the QCD backgrounds.

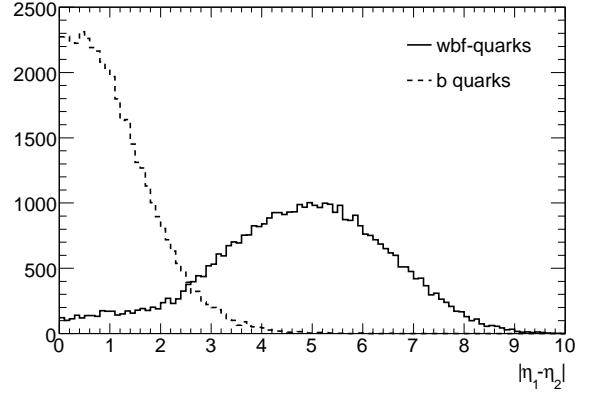


FIG. 13: Distribution of the absolute distance in pseudo-rapidity between WBF quark pair and b-quark pair for a 115 GeV/c<sup>2</sup> Higgs mass at 14 TeV  $pp$  collisions.

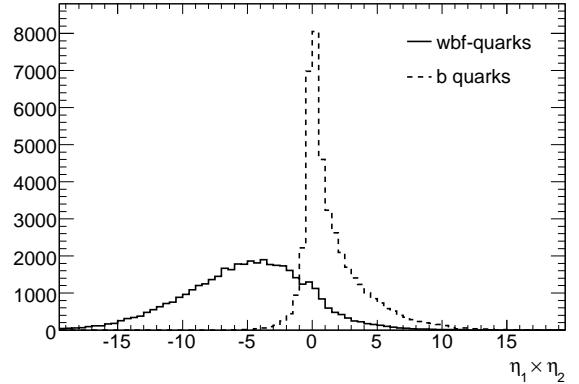


FIG. 14: Distribution of the product of pseudo-rapidities,  $\eta_1 \times \eta_2$ , between WBF quark pair and b-quark pair for a 115 GeV/c<sup>2</sup> Higgs mass at 14 TeV  $pp$  collisions.

*Transverse Momentum:* We required the highest  $p_T$  WBF jet to have a  $p_T$  greater than 55 GeV/c to remove events with a ‘soft’ tagged jet which are copiously produced in QCD background events. The  $p_T$  distributions of the highest  $p_T$  WBF jet for a 115 GeV/c<sup>2</sup> mass Higgs signal and the background are presented in Figure 17.

*Geometrical Distributions:* Although the WBF tagger finds the best jet pair which satisfies the geometrical distributions of the signal WBF jets, the  $\Delta\eta$  distribution, shown in Figure 18, provides additional discrimination between signal and background. Consequently, we required that the  $\Delta\eta$  of the WBF pair be greater than 3.25.

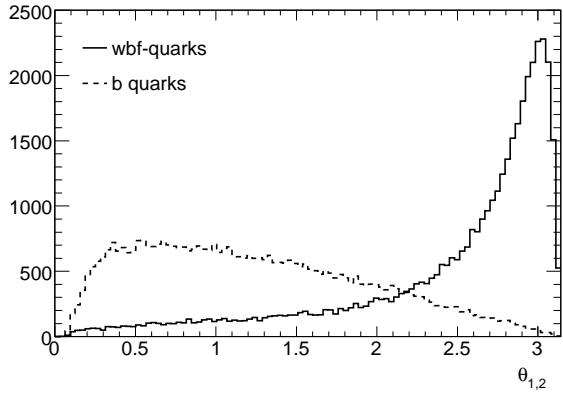


FIG. 15: Distribution of the 3-dimensional angle between the two jets ( $\theta_{1,2}$ ) between WBF quark pair and b-quark pair for a 115  $\text{GeV}/c^2$  Higgs mass at 14 TeV  $pp$  collisions.

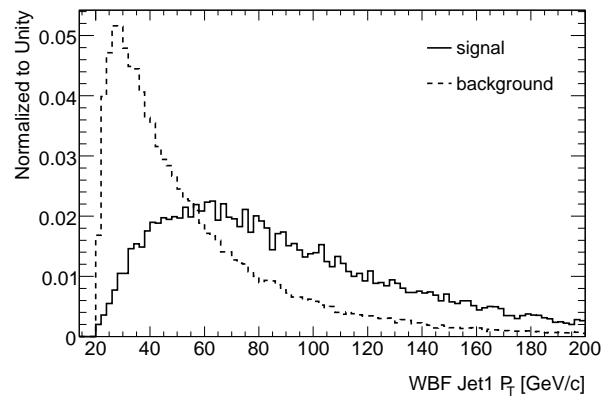


FIG. 17: Distribution of the transverse momentum of the highest transverse momentum WBF jet for a 115  $\text{GeV}/c^2$  Higgs mass at 14 TeV  $pp$  collisions.

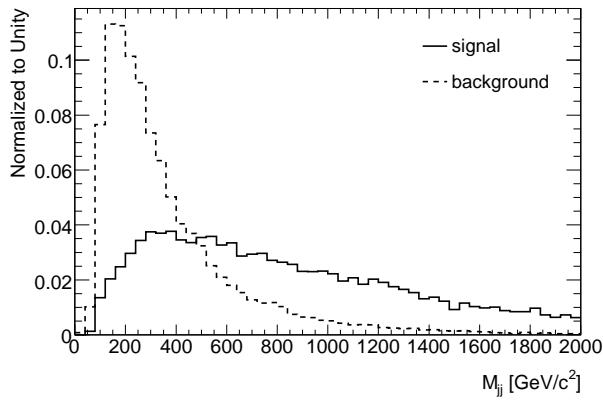


FIG. 16: Distribution of the invariant mass of the two WBF jets for a 115  $\text{GeV}/c^2$  Higgs mass at 14 TeV  $pp$  collisions.

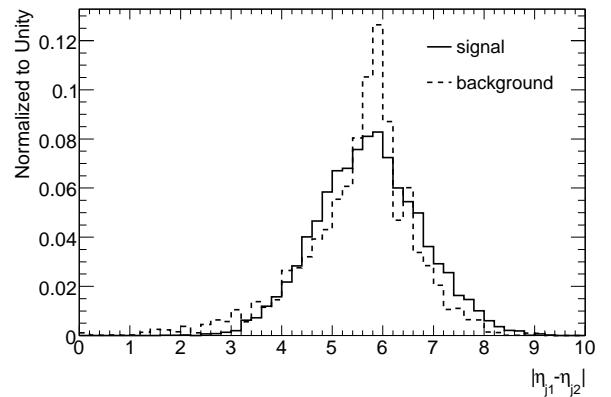


FIG. 18: Distribution of the absolute distance in pseudo-rapidity,  $|\Delta\eta_{1,2}| = |\eta_1 - \eta_2|$ , between WBF jets for a 115  $\text{GeV}/c^2$  Higgs mass at 14 TeV  $pp$  collisions.

#### D. B-jets Identification

In order to estimate the expected b-jet identification at the LHC experiments, we assumed 60% b-tagging efficiency within  $|\eta| < 2.5$ . This b-tagging efficiency corresponds to approximately a 10 and 200 rejection factor for light-jets<sup>2</sup> and c-jets, respectively [7].

We simulated the expected performance of the b-tagging by first matching jets which originate from the matrix-element b-quark. Once the jets are matched, we randomly generated the efficiency using a uniform distribution. Jets which passed based on the assumed b-tagging efficiency were identified as a b-jet. Similarly, we simulated the expected fake rate from light and

c jets by using the same prescription assuming the aforementioned rejection factors. In order to retain the full Monte Carlo statistics, we required that each event produce at least two b-jets. Consequently, we kept count of the number of iterations required to satisfy this criteria and we normalized the expected number of events accordingly. Once the b-jets were identified, we applied the cuts listed below.

*Transverse Momentum:* Similar to the WBF jets, the QCD background has relatively ‘soft’  $p_T$  b-jets compared to those in the signal events, as shown in Figures 19 and 20. However, applying a high  $p_T$  cut on the b-jet candidates significantly shapes the invariant mass of the two b-jets in the background, as shown in Figures 21 and 22. Consequently, we only applied a low  $p_T$  cut of 20  $\text{GeV}/c$  on both b-jet candidates.

<sup>2</sup> Jets originating from u,d, and s quarks and gluons.

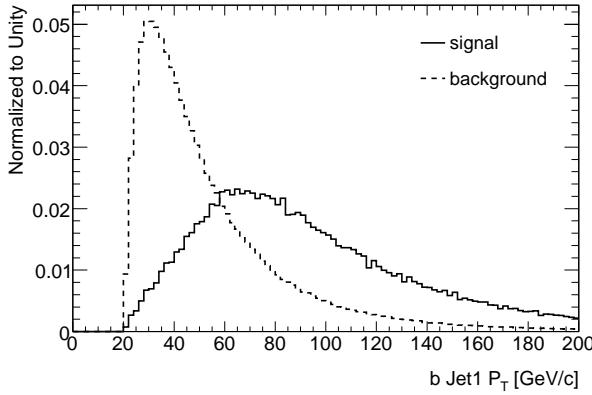


FIG. 19: Distribution of the transverse momentum of the highest transverse momentum b-jet for a 115  $\text{GeV}/c^2$  Higgs mass at 14 TeV  $pp$  collisions.

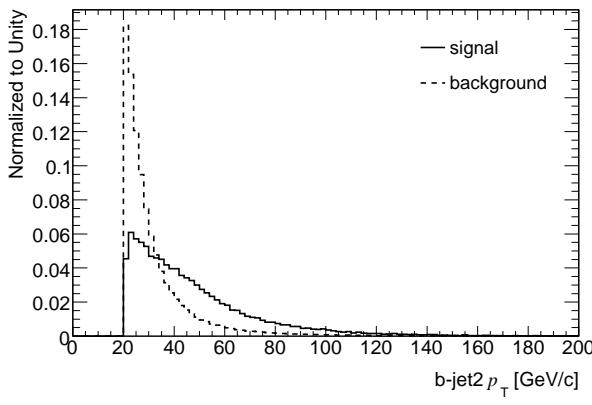


FIG. 20: Distribution of the transverse momentum of the second highest transverse momentum b-jet for a 115  $\text{GeV}/c^2$  Higgs mass at 14 TeV  $pp$  collisions.

*Geometrical Distributions:* In contrast to the WBF jets, the b-jets are generally close in  $\eta$  as shown in Figure 23. Accordingly, we required that the b-jets are within  $\Delta\eta < 1.25$ . Additionally, we apply a cuts on the  $\eta$  product of the two b-jets and the angle between the boost and the decay axis of the  $H \rightarrow b\bar{b}$  which are shown in Figure 24 and 25 respectively.

*Invariant Mass:* The most discriminating variable in this analysis is the invariant mass of the two b-jets. Signal events peak at the nominal Higgs mass while the QCD background has a broad continuum distribution as shown in Figure 21. In order to estimate the significance of this analysis, we counted candidates in a two b-jet invariant mass window near the nominal signal Higgs mass. The lower limit of the mass window is 100, 108, and 117  $\text{GeV}/c^2$  and the upper limit of the mass window is 125, 136, and 147  $\text{GeV}/c^2$  optimized for a Higgs mass of

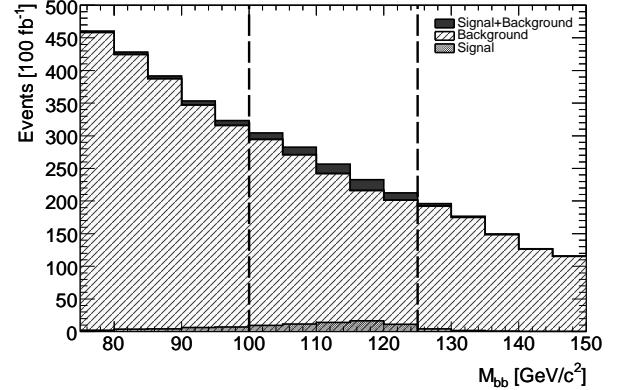


FIG. 21: Distribution of the invariant mass of the two b-jets with all selection criteria itemized in Table VIII with the additional requirement of  $p_T > 20 \text{ GeV}/c$  on both b-jets for a 115  $\text{GeV}/c^2$  Higgs mass at 14 TeV  $pp$  collisions.

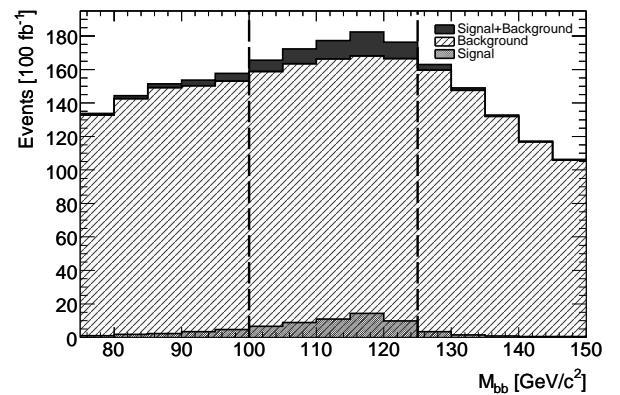


FIG. 22: Distribution of the invariant mass of the two b-jets with all selection criteria itemized in Table VIII after applying a  $p_T$  cut of 60  $\text{GeV}/c$  on the highest  $p_T$  b-jet for a 115  $\text{GeV}/c^2$  Higgs mass at 14 TeV  $pp$  collisions.

115, 125 and 135  $\text{GeV}/c^2$ , respectively.

## E. B-jet Calibration

The results of this analysis strongly rely on the ability to identify jets originating from b-quarks and accurately reconstruct their 4-momentum. However, the b-jet linearity and resolution are noticeably worse than light-quark jets as described in Section IV B. Here, we present a calibration technique to improve the b-jet performance which consequently corrects the invariant mass of the two b-jets.

We have implemented the *numerical inversion* method which corrects the transverse momentum of the b-jets by applying a multiplicative scale factor derived from the

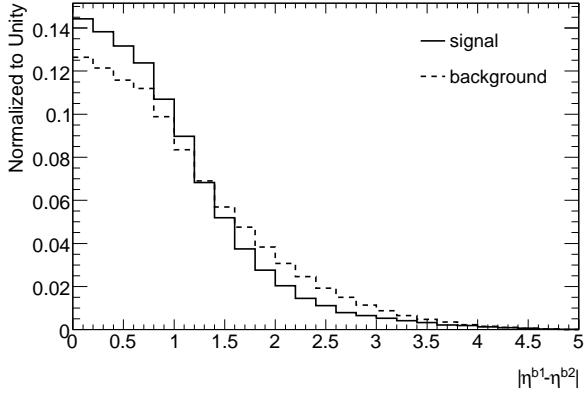


FIG. 23: Distribution of the absolute distance in pseudo-rapidity between b-jets for a 115 GeV/c<sup>2</sup> Higgs mass at 14 TeV pp collisions.

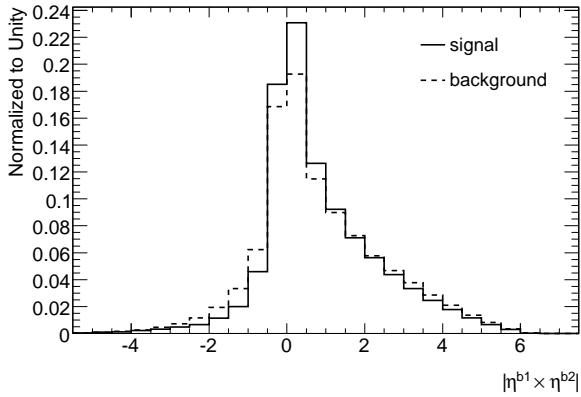


FIG. 24: Distribution of the product of pseudo-rapidity between b-jets for a 115 GeV/c<sup>2</sup> Higgs mass at 14 TeV pp collisions.

ratio of the transverse momentum between the reconstructed jet and the original b-quark. The scale factors were derived in bins of  $\eta$  and  $p_T$  using the  $b\bar{b}+1\text{parton}+\gamma$  and  $b\bar{b}+2\text{partons}+\gamma$  background samples. Additionally, two sets of calibration scale factors were derived for b-jets with and without matching muons. A muon is considered matched to a jet if  $\Delta R_{j\mu} < 0.4$  with  $p_T(\mu)$  greater than 5 GeV/c. The result of the calibration gave mean values of the invariant mass of the signal events with a Higgs mass of 115 GeV/c<sup>2</sup> shifts from 106.4 GeV/c<sup>2</sup> to 112.6 GeV/c<sup>2</sup> while slightly reducing the relative RMS from 14.98 % to 13.33 %. We have applied this method to our b-jets to improve the result on the reconstruction of invariant mass resonances. In Figure 26, we can see the difference in a 115 GeV/c<sup>2</sup> Higgs mass reconstruction before and after the calibration.

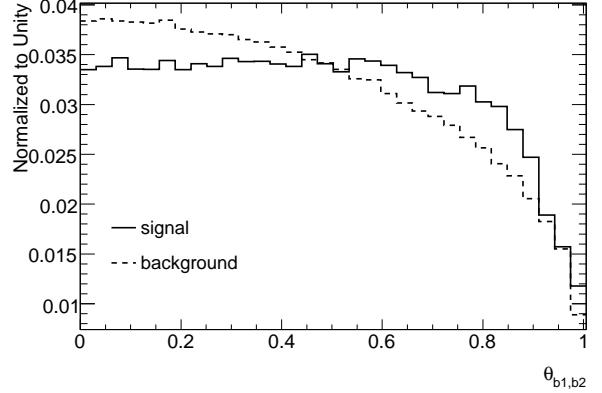


FIG. 25: Distribution of the cosine of the angle between the boost and decay axis of the  $H \rightarrow b\bar{b}$  candidates for a 115 GeV/c<sup>2</sup> Higgs mass at 14 TeV pp collisions.

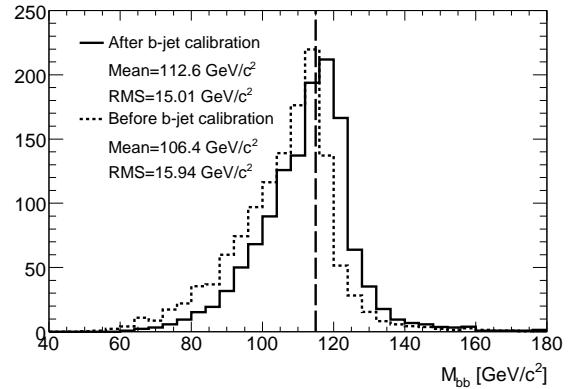


FIG. 26: Reconstruction of the invariant mass of the  $b\bar{b}$  pairs for a 115 GeV/c<sup>2</sup> Higgs mass at 14 TeV pp collisions.

## F. Central Jet Veto

A key aspects of the WBF Higgs process is its electroweak nature. At leading-order the signal process does not have any color flow between the interacting quarks. In contrast, the majority of the backgrounds have QCD radiation between interacting quarks. Removing events with jet activity in the region between the WBF jets provides a potentially powerful tool to suppress backgrounds. In addition to the hard interaction of interest, each event includes an underlying event, consequently, the choice of showering, hadronization, and UE models employed in the Monte Carlo samples can potentially impact the efficacy of the central jet veto (CJV). We investigated two techniques to optimize the central jet veto.

- *Fixed η Window:* Events are vetoed if additional jets above a given  $p_T$  threshold are found within a fixed  $\eta$  window.

- *Dynamic  $\eta$  Window*: Similar to the fixed  $\eta$  window, however, the  $\eta$  window is defined by the  $\eta$  of the two WBF jets event-by-event.

The results from this study were determined using a 115 GeV/c<sup>2</sup> Higgs mass signal sample and the  $b\bar{b}$ +2partons+ $\gamma$  background samples. Both samples were produced using the nominal *Perugia* tune. For the *fixed*  $\eta$  window and the  $\gamma$ , we scanned the  $p_T \times |\eta|$  plane and found that a veto on jets within  $|\eta| < 2$  and  $p_T$  greater than 25 GeV/c was optimal. For the *dynamic*  $\eta$  window, we scanned the  $p_T$  threshold and found the optimal value to be 25 GeV/c. The *fixed*  $\eta$  window technique provides approximately a 16% increase in signal significance - a modest 5% improvement over the *dynamic*  $\eta$  window technique.

## V. SYSTEMATIC UNCERTAINTIES

In this section, we considered several sources of systematic uncertainties associated with the signal and background cross-sections and the choice of Monte Carlo tunes.

### A. Factorization/Renormalization Scale

For the analysis, the nominal parametrization for the renormalization/factorization scale is listed in Section III. Within the ALPGEN program, the renormalization/factorization scales are linearly correlated ( $\mu_F = \mu_R = \mu$ ). As such, anti-correlated relationship between factorization and renormalization scales was not considered. In order to estimate the uncertainty related to the parametrization of the scales, we scanned the various ALPGEN parametrizations and multiplied the parameterization by 0.5 and 2. The result from these variations for a 115 GeV/c<sup>2</sup> Higgs mass were within 5% of the results using the nominal settings. Additionally, we performed the same methodology on the background and the results are shown in Table V.

### B. Parton Density Function

The parton distribution functions (PDFs) of the nucleon are central to determining the cross-section of the processes at proton-proton collisions. We used the full group of 40 CTEQ6M sets which allowed the determination of the PDF systematics uncertainty using the prescription defined in [17] using the Equation 4.

$$\Delta\sigma = \frac{1}{2} \sqrt{\sum_{i=1}^{20} (\sigma_{2i} - \sigma_{2i-1})^2}, \quad (4)$$

Here  $\sigma_i$  are the cross-sections based on the  $i^{th}$  PDF sets. For the Higgs process we found that the contribution for

the PDF uncertainty is of the order of  $\sim 4\%$ .

From the different background processes, the PDF uncertainty ranges from 3.52% to 3.89% and are shown in Table V.

Number of Partons	$\sigma$ [pb]	$\frac{\Delta\sigma_{scale}}{\sigma}$ [%]	$\frac{\Delta\sigma_{PDF}}{\sigma}$ [%]
$b\bar{b}+n\text{parton}+\gamma$			
1	1088	+34.5 -38.8	3.89
2	658	+52.4 -50.8	3.58
$n\text{parton}+\gamma$			
3	45789	+ 36.1 -22.8	3.78
4	17595	+ 59.7 -31.2	3.16
$Z(\rightarrow q\bar{q})+n\text{parton}+\gamma$			
1	27	+15.9 -12.1	3.52
2	18	+ 32.5 -24.4	3.73

TABLE V: Nominal cross section, factorization and renormalization scales, and PDF uncertainties for backgrounds Monte Carlo at 14 TeV  $pp$  collisions.

### C. Showering, Hadronization, and the Underlying Event Model

In order to estimate the systematic uncertainty originating from showering, hadronization, and the UE model, we processed the signal and background ALPGEN 4-vectors using three variations of the *Perugia* Tunes which have been available since PYTHIA 6.4.20 [10]. We considered the *Perugia* 0 as the nominal tune for this analysis and the *Perugia* ‘soft’ and ‘hard’ tunes for this systematic study. The *Perugia* variations are said to provide ‘uncertainty bands’ and indicate an uncertainty of approximately 15% or less on the nominal tune [18].

As stated in Section III, the MLM prescription provides the ability to merge samples from different hard-parton multiplicity without double counting. However, the MLM prescription is sensitive to the Monte Carlo tune. Consequently, the *Perugia* tunes provide an estimation of the uncertainty of the MLM efficiency, as shown in Table VI. From the different background processes, the MLM efficiency uncertainty ranges from 10% to 20%.

Additionally, we investigated the properties of sput-

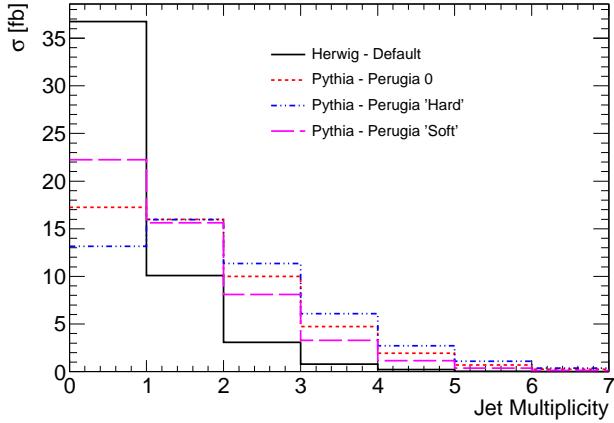


FIG. 27: Comparison of the jet multiplicity for jet not originating from the hard process between HERWIG and the PYTHIA tunes for a  $115 \text{ GeV}/c^2$  Higgs mass at  $14 \text{ TeV}$   $pp$  collisions.

rious jets between HERWIG and the PYTHIA tunes within the signal and  $b\bar{b}+2\text{partons}+\gamma$  samples. Comparing the multiplicity for spurious jets between HERWIG and the PYTHIA tunes a noticeable difference we observed, as shown in Figures 27 and 30. For the HERWIG tune, approximately 70% of signal events and 50% of  $b\bar{b}+2\text{partons}+\gamma$  events do not have any additional jets while for the PYTHIA tunes both signal and background have approximately 40% of events in the zero jet bin. From Figures 28 and 31, we can see that the  $p_T$  distribution in signal and background are different between HERWIG and PYTHIA which provides a more effective CJV using HERWIG. Additionally, there are 3.5-6.0 times more spurious central jets in the PYTHIA signal sample compared to HERWIG, as shown in Figure 29. In contrast, in the  $b\bar{b}+2\text{partons}+\gamma$  sample there is only 1.5-2.0 times more spurious central jets in PYTHIA compared to HERWIG, as shown in Figure 32. Consequently, the results of our study indicate that the original estimation [8] on the efficacy of the CJV was to optimistic and only a modest improvement in significance is expected.

In summary, the *Perugia* tunes affect the expected number of signal and background events, as shown in Table VII, yielding an uncertainty of 15.6% and 25.5%, respectively. However, the overall effect on the signal significance is approximately 4%, as shown in Table VII.

## VI. RESULTS

Tables X, XI, and XII give the expected number of events for  $100 \text{ fb}^{-1}$  of data at  $14 \text{ TeV}$  collision energy after the application of successive cuts in the event selection out-

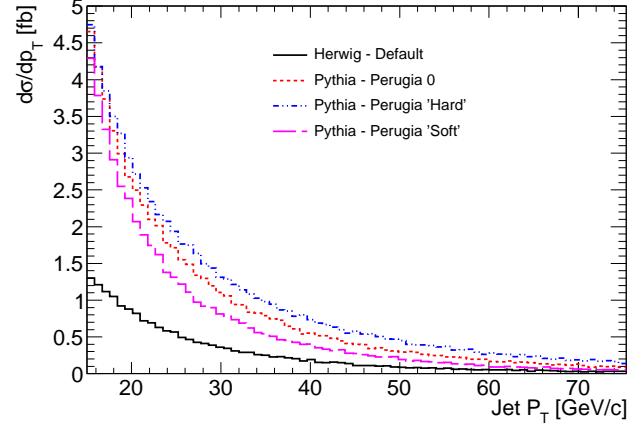


FIG. 28: Comparison of the jet  $p_T$  distribution for jet not originating from the hard process between HERWIG and the PYTHIA tunes for a  $115 \text{ GeV}/c^2$  Higgs mass at  $14 \text{ TeV}$   $pp$  collisions.

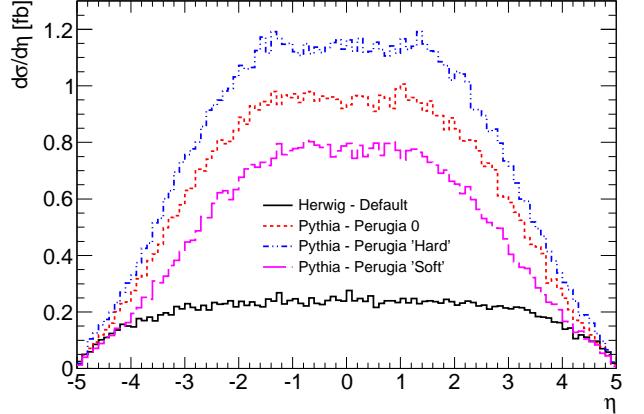


FIG. 29: Comparison of the jet  $\eta$  distribution for jet not originating from the hard process between HERWIG and the PYTHIA tunes for a  $115 \text{ GeV}/c^2$  Higgs mass at  $14 \text{ TeV}$   $pp$  collisions.

lined in Section IV and listed in Table VIII for a  $115 \text{ GeV}/c^2$ ,  $125 \text{ GeV}/c^2$ ,  $135 \text{ GeV}/c^2$  Higgs mass, respectively. Additionally, the signal significance derived from the aforementioned tables are shown in Table IX.

## VII. SUMMARY

In this paper, we presented the prospect for observing a light SM Higgs boson decaying to two b-quarks via WBF production with an associated photon at the LHC for  $14 \text{ TeV}$  collision energies. We analyzed the signal and primary backgrounds after showering, hadronization, and included a UE model. We studied various jet

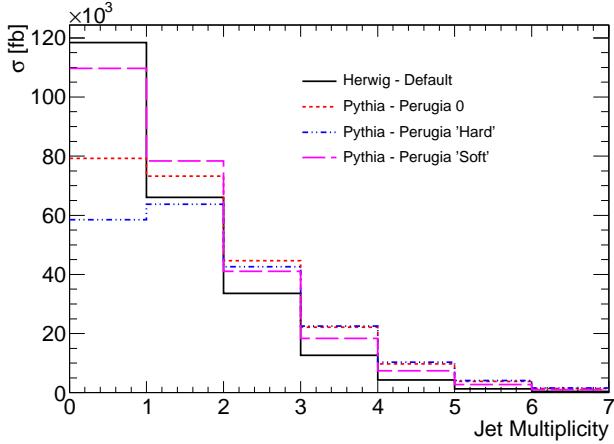


FIG. 30: Comparison of the jet multiplicity for jet not originating from the hard process between HERWIG and the PYTHIA tunes for  $b\bar{b}+2\text{partons}+\gamma$  events at 14 TeV  $pp$  collisions.

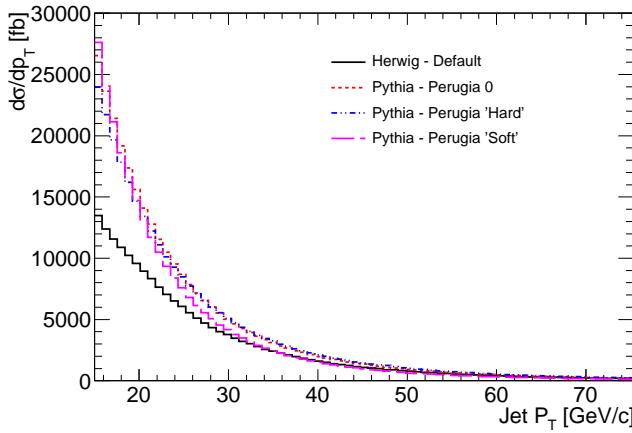


FIG. 31: Comparison of the jet  $p_T$  distribution for jet not originating from the hard process between HERWIG and the PYTHIA tunes for  $b\bar{b}+2\text{partons}+\gamma$  events at 14 TeV  $pp$  collisions.

algorithms and concluded that ANTI-KT6 provided the best overall performance. We developed a likelihood WBF tagger in order to distinguish the Higgs b-jets and the WBF jets. We simulated the b-jet efficiency and light jet fake rate based on the latest expected detector performance studies. For the b-jet candidates, we performed a calibration using the *numerical inversion* technique in order to provide a reconstructed invariant mass at the nominal Higgs mass.

Three sources of uncertainty were investigated: choice of factorization and renormalization, Monte Carlo tunes, and input PDFs. The largest uncertainty in this analysis was the background cross-section of the  $b\bar{b}+2\text{partons}+\gamma$

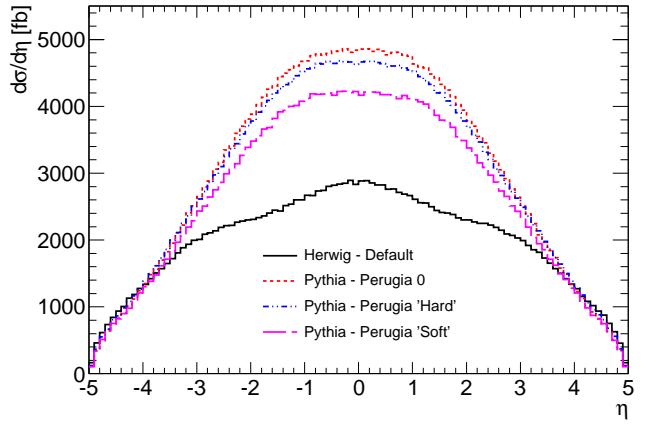


FIG. 32: Comparison of the jet  $\eta$  distribution for jet not originating from the hard process between HERWIG and the PYTHIA tunes for  $b\bar{b}+2\text{partons}+\gamma$  events at 14 TeV  $pp$  collisions.

Number of Partons	MLM Efficiency [%]			$\frac{\Delta\sigma_{MLM}}{\sigma} [\%]$
	Nominal	Soft	Hard	
$b\bar{b}+n\text{parton}+\gamma$				
1	37.9	29.5	44.6	20.2
2	35.7	31.0	39.4	11.8
$n\text{parton}+\gamma$				
3	20.5	17.2	25.3	19.3
4	17.8	15.3	21.0	15.8
$Z(\rightarrow q\bar{q})+n\text{parton}+\gamma$				
1	40.6	34.2	47.0	15.8
2	44.5	39.8	48.6	10.0

TABLE VI: Background MLM uncertainties originating from Monte Carlo tunes for 14 TeV  $pp$  collisions.

background which varies by approximately  $\pm 50\%$ . Consequently, for a 115  $\text{GeV}/c^2$  mass Higgs the significance can potentially be as large as  $\sim 2.6$  assuming a more conservative factorization and renormalization scale. The choice of Monte Carlo and Monte Carlo tune has several effects on the analysis such as the overall number of expected events in signal and background and efficacy of CJV. We found that the previous estimation on efficacy of the CJV using HERWIG was too optimistic. The CJV using HERWIG provides a 49% increase in the signal significance while PYTHIA only increase the signal significance by 16%. Moreover, based on the latest ATLAS charge multiplicity results [19] we conclude that the proper Monte Carlo tune is between the *Perugia* nominal and “hard” tunes. The uncertainty originating from the input PDFs is approximately  $\pm 5\%$  for both signal and background. This analysis has several large theoretical uncertainties and studies using early  $pp$  data

Estimated Results	Perugia Tunes		
	Nominal	Soft	Hard
Signal Events ( $S$ )	68 $\pm$ 1	56 $\pm$ 1	78 $\pm$ 2
Background Events ( $B$ )	1336 $\pm$ 35	1072 $\pm$ 33	2013 $\pm$ 53
$S/\sqrt{B}$	1.86 $\pm$ 0.06	1.71 $\pm$ 0.06	1.74 $\pm$ 0.05

TABLE VII: Expected signal and background events and overall significance uncertainties originating from Monte Carlo tunes for a 115  $\text{GeV}/c^2$  Higgs mass at 14  $\text{TeV}$   $pp$  collisions. Only Monte Carlo statistical errors are quoted.

Cut #	Selection Criteria
1	$p_T(\gamma) > 30 \text{ GeV}/c$
2	# of Jets $\geq 4$
3	# of Central Jets $\geq 2$
4	Two b-jets
5	$p_T(j1) > 55 \text{ GeV}/c$
6	$M(j1, j2) > 695.0 \text{ GeV}/c^2$
7	$\Delta\eta(j1, j2) > 3.25$
8	$\theta(b1, b2) < 0.92$
9	$\Delta\eta(b1, b2) < 1.25$
10	$\eta(b1) \times \eta(b2) > -0.25$
11	
i) $m_h = 115 \text{ GeV}/c^2$	$m_{bb} > 100 \text{ GeV}/c^2$
ii) $m_h = 125 \text{ GeV}/c^2$	$m_{bb} > 108 \text{ GeV}/c^2$
iii) $m_h = 135 \text{ GeV}/c^2$	$m_{bb} > 117 \text{ GeV}/c^2$
12	
i) $m_h = 115 \text{ GeV}/c^2$	$m_{bb} < 125 \text{ GeV}/c^2$
ii) $m_h = 125 \text{ GeV}/c^2$	$m_{bb} < 136 \text{ GeV}/c^2$
iii) $m_h = 135 \text{ GeV}/c^2$	$m_{bb} < 147 \text{ GeV}/c^2$
13	Central Jet Veto

TABLE VIII: Selection Criteria. Here cuts 11 and 12 are apply to the appropriate Higgs mass sample.

at LHC could provide guidance as to the appropriate choice of factorization and renormalization and Monte Carlo tune.

A light SM Higgs boson will be very challenging to identify at the LHC and several channels will be required to confirm any observation. Consequently, this analysis provides an important contribution to the overall sensitivity for the  $H \rightarrow b\bar{b}$  decay mode.

## VIII. ACKNOWLEDGMENTS

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Estimated Results	Higgs Mass		
	115	125	135
Signal Events ( $S$ )	68 $\pm$ 1	58 $\pm$ 1	33 $\pm$ 1
Background Events ( $B$ )	1337 $\pm$ 35	1341 $\pm$ 38	1210 $\pm$ 37
$S/\sqrt{B}$	1.86 $\pm$ 0.06	1.58 $\pm$ 0.05	0.95 $\pm$ 0.04

TABLE IX: Expected signal and background events and overall significance uncertainties for Higgs mass of 115, 125, and 135  $\text{GeV}/c^2$  for 14  $\text{TeV}$   $pp$  collisions. Only Monte Carlo statistical errors are quoted.

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[19] The ATLAS Collaboration, arXiv:1003.3124.

Cut #	$m_h$ 115 $\text{GeV}/c^2$	$bb+2\text{jets}+\gamma$	$bb+1\text{jet}+\gamma$	$4\text{jets}+\gamma$	$3\text{jets}+\gamma$	$z+2\text{jets}+\gamma$	$z+1\text{jet}+\gamma$
None	5096	23503936	41227936	313253568	815215040	812711	1099440
1	2460 (48%)	8631124 (37%)	11964605 (29%)	116548496 (37%)	254604944 (31%)	363997 (45%)	409825 (37%)
2	1835 (75%)	4744277 (55%)	622729 (5%)	80952640 (69%)	19777422 (8%)	238115 (65%)	28732 (7%)
3	1768 (96%)	4649472 (98%)	608376 (98%)	79378192 (98%)	19324588 (98%)	232430 (98%)	27220 (95%)
4	438 (25%)	499215 (11%)	48787 (8%)	76163 (0%)	10310 (0%)	7405 (3%)	608 (2%)
5	336 (77%)	230068 (46%)	9412 (19%)	30275 (40%)	2181 (21%)	4035 (54%)	149 (24%)
6	221 (66%)	66128 (29%)	1182 (13%)	7766 (26%)	649 (30%)	901 (22%)	13 (8%)
7	219 (99%)	64744 (98%)	1182	7707 (99%)	648	815 (90%)	13
8	215 (98%)	60848 (94%)	1115 (94%)	7364 (96%)	583 (90%)	788 (97%)	12
9	179 (83%)	36085 (59%)	534 (48%)	3390 (46%)	253 (43%)	667 (85%)	9 (68%)
10	175 (98%)	34991 (97%)	533	3066 (90%)	253	659 (99%)	8 (97%)
11	129 (74%)	13131 (38%)	123 (23%)	1465 (48%)	65 (26%)	123 (19%)	1 (15%)
12	110 (86%)	4202 (32%)	26 (21%)	369 (25%)	11 (17%)	72 (58%)	1 (95%)
13	68 (62%)	1182 (28%)	13 (50%)	110 (30%)	6 (49%)	25 (35%)	1 (64%)

TABLE X: Number of expected events for  $100 \text{ fb}^{-1}$  of integrated luminosity for a  $115 \text{ GeV}/c^2$  mass Higgs and background samples at each step of the selection process for  $14 \text{ TeV}$   $pp$  collisions. The relative efficiency for each selection step is given in parentheses. The Cut # is defined in Table VIII.

Cut #	$m_h$ 125 $\text{GeV}/c^2$	$bb+2\text{jets}+\gamma$	$bb+1\text{jet}+\gamma$	$4\text{jets}+\gamma$	$3\text{jets}+\gamma$	$z+2\text{jets}+\gamma$	$z+1\text{jet}+\gamma$
None	4087	23503936	41227936	313253568	815215040	812711	1099440
1	1989 (49%)	8631124 (37%)	11964605 (29%)	116548496 (37%)	254604944 (31%)	363997 (45%)	409825 (37%)
2	1522 (77%)	4744277 (55%)	622729 (5%)	80952640 (69%)	19777422 (8%)	238115 (65%)	28732 (7%)
3	1466 (96%)	4649472 (98%)	608376 (98%)	79378192 (98%)	19324588 (98%)	232430 (98%)	27220 (95%)
4	371 (25%)	498435 (11%)	49093 (8%)	77162 (0%)	10467 (0%)	7427 (3%)	607 (2%)
5	282 (76%)	229971 (46%)	9396 (19%)	29671 (38%)	3021 (29%)	4021 (54%)	143 (24%)
6	187 (66%)	65972 (29%)	1400 (15%)	7374 (25%)	849 (28%)	902 (22%)	14 (10%)
7	186 (99%)	64561 (98%)	1399	7296 (99%)	848	822 (91%)	14
8	182 (98%)	60720 (94%)	1304 (93%)	6783 (93%)	836 (99%)	792 (96%)	14
9	148 (81%)	35765 (59%)	711 (55%)	3883 (57%)	446 (53%)	668 (84%)	10 (70%)
10	144 (98%)	34670 (97%)	710	3645 (94%)	446	659 (99%)	9 (97%)
11	108 (75%)	11533 (33%)	164 (23%)	1795 (49%)	241 (54%)	84 (13%)	1 (8%)
12	94 (87%)	4242 (37%)	57 (35%)	506 (28%)	6 (2%)	38 (45%)	1 (96%)
13	58 (62%)	1207 (28%)	28 (48%)	86 (17%)	6 (93%)	13 (35%)	1 (94%)

TABLE XI: Number of expected events for  $100 \text{ fb}^{-1}$  of integrated luminosity for a  $125 \text{ GeV}/c^2$  mass Higgs and background samples at each step of the selection process for  $14 \text{ TeV}$   $pp$  collisions. The relative efficiency for each selection step is given in parentheses. The Cut # is defined in Table VIII.

Cut #	$m_h$ 135 $\text{GeV}$	$bb+2\text{jets}+\gamma$	$bb+1\text{jet}+\gamma$	$4\text{jets}+\gamma$	$3\text{jets}+\gamma$	$z+2\text{jets}+\gamma$	$z+1\text{jet}+\gamma$
None	2270	23503936	41227936	313253568	815215040	812711	1099440
1	1116 (49%)	8631124 (37%)	11964605 (29%)	116548496 (37%)	254604944 (31%)	363997 (45%)	409825 (37%)
2	876 (78%)	4744277 (55%)	622729 (5%)	80952640 (69%)	19777422 (8%)	238115 (65%)	28732 (7%)
3	846 (97%)	4649472 (98%)	608376 (98%)	79378192 (98%)	19324588 (98%)	232430 (98%)	27220 (95%)
4	216 (26%)	498158 (11%)	49244 (8%)	76238 (0%)	9508 (0%)	7350 (3%)	606 (2%)
5	166 (77%)	229746 (46%)	9634 (20%)	28590 (38%)	1930 (20%)	4025 (55%)	144 (24%)
6	111 (67%)	66282 (29%)	1333 (14%)	6878 (24%)	387 (20%)	890 (22%)	12 (8%)
7	111 (99%)	64810 (98%)	1333	6844	386	804 (90%)	12
8	107 (97%)	61105 (94%)	1271 (95%)	6391 (93%)	372 (96%)	773 (96%)	12
9	86 (80%)	35869 (59%)	598 (47%)	3431 (54%)	172 (46%)	658 (85%)	9 (76%)
10	84 (98%)	34714 (97%)	596	3291 (96%)	169 (99%)	648 (98%)	9 (97%)
11	62 (74%)	10053 (29%)	118 (20%)	1405 (43%)	23 (14%)	69 (11%)	0 (1%)
12	54 (87%)	3728 (37%)	40 (34%)	549 (39%)	7 (29%)	27 (39%)	0 (87%)
13	33 (61%)	1091 (29%)	27 (69%)	76 (14%)	5 (74%)	11 (41%)	0 (20%)

TABLE XII: Number of expected events for  $100 \text{ fb}^{-1}$  of integrated luminosity for a  $135 \text{ GeV}/c^2$  mass Higgs and background samples at each step of the selection process for  $14 \text{ TeV}$   $pp$  collisions. The relative efficiency for each selection step is given in parentheses. The Cut # is defined in Table VIII.